

INSTRUCTION REPORT 7

# DESCRIPTION AND APPLICATION OF AIRFIELD CONE PENETROMETER

by

W. B. Fenwick



October 1965

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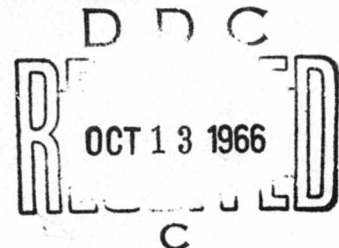
U. S. Army Materiel Command

Conducted by

U. S. Army Engineer Waterways Experiment Station

CORPS OF ENGINEERS

Vicksburg, Mississippi

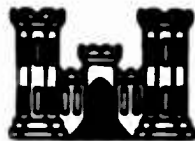


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**Vicksburg, Mississippi**

**ARMY MAC VICKSBURG, MISS**

### Foreword

This report was prepared as a part of the work authorized by the U. S. Army Materiel Command in its letter (RD-SP-C) dated 14 June 1965, subject, "FY 1966 Program Guidance (Task -01)."

Engineers of the Soils Division, U. S. Army Engineer Waterways Experiment Station (WES), who were actively engaged in the planning, testing, and analysis phases of the various studies that served as a basis for preparation of this report were Messrs. W. J. Turnbull, A. A. Maxwell, W. L. McInnis, R. G. Ahlvin, C. D. Burns, and D. N. Brown. This report was written by Mr. W. B. Fenwick.

Director of the WES during the preparation of this report was Col. John R. Oswalt, Jr., CE. Mr. J. B. Tiffany was Technical Director.

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# DESCRIPTION AND APPLICATION OF AIRFIELD CONE PENETROMETER

## Introduction

### The airfield cone penetrometer

1. The airfield cone penetrometer is an instrument which will assist engineering personnel in determining an index of soil strengths for various military and civil applications. The forerunner of the airfield penetrometer was the trafficability penetrometer developed in 1946 by the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. The airfield penetrometer, also developed by WES, can be used as an aid in the assessment of the load-supporting capability of forward landing strips and the trafficability of ground supply routes, and can also be an aid in maintaining field control during construction operations. It is compact, sturdy, and simple enough to be used by persons who are relatively inexperienced in the techniques of soil-strength determination.

### Purpose and scope of report

2. The purpose of this report is to describe the airfield cone penetrometer, its use, and the application of data obtained by its use. The report includes information which will assist in solving specific trafficability problems. Also procedures are presented for using the airfield penetrometer to measure soil strength and for correlating soil strength with the number of passes that can be made by aircraft having various wheel loads and tire pressures.

### Definition of terms

3. Certain terms used in this report are defined as follows:

- a. Airfield index. A measure of soil strength obtained with the airfield cone penetrometer.
- b. Aircraft pass. One takeoff or one landing.
- c. Coverage. One pass of a load wheel over each point within a traffic lane. In the case of large, multiple-wheel aircraft, as few as two passes may be required to apply one coverage; for smaller, single-wheel aircraft, as many as 10 to 20 passes may be required.
- d. Single-wheel load. The gross load supported by a single wheel of a main landing gear.

- e. Equivalent single-wheel load. The load on a single-wheel main gear which will produce effects equivalent to those produced by the total load on a multiple-wheel assembly.

#### Correlation of Airfield Index with CBR

4. The California Bearing Ratio (CBR) is widely used to express values of soil strength; many flexible airfield and highway pavements and nearly all expedient-surfaced and unsurfaced roads or emergency landing strips are built according to the CBR empirical design procedure. However, the bulk and weight of the CBR apparatus and the considerable time involved in conducting the CBR test make the method impractical for rapidly evaluating an airstrip. The airfield cone penetrometer was therefore developed as an expedient strength reconnaissance and evaluation instrument. In order to take advantage of available data on the soil strength or CBR required to support various aircraft which have been gathered over many years, it was necessary to correlate the airfield index with CBR. CBR's and airfield indexes were obtained from many sites and correlated; it was found that the correlations varied somewhat for the different sites. Therefore, users of the data presented in this report should be thoroughly aware of the warnings given later in paragraph 22.

#### Description, Use, and Maintenance of Airfield Penetrometer

##### Description

5. The airfield cone penetrometer is a probe-type instrument designed to measure soil strength. It is shown in use in fig. 1 and in detail in plate 1. It consists of a 30-deg right circular cone with a base diameter of 1/2 in. (area equals 0.196 sq in.) mounted on a graduated staff; on the opposite end of the staff are a spring, a load indicator, and a handle. The overall length of the assembled penetrometer is about 36-1/8 in. For ease in carrying, the penetrometer can be disassembled into three main pieces: two extension staffs, each 12-5/8 in. long, and one piece 14-3/4 in. long which includes the cone, handle, spring, and load indicator. Two wrenches and an extra cone accompany the instrument and can be carried in the handle. The carrying case for the three pieces is made of heavy duck.



The penetrometer (including the wrenches) weighs about 2.6 lb.

6. The staffs are graduated in 2-in. increments and are provided with wrench flats to facilitate assembly and disassembly. The cone also has a wrench flat to permit disassembly with an open-end wrench. The handle is a metal cylinder which slips through a ring at the top of the instrument. When the instrument is disassembled, the handle fits over the bottom end of the largest piece and protects the cone. The spring, consisting of two separate sets of interwound coils which act as a single unit, is stretched (tension) directly in proportion to the load applied to the handle. The load-indicating device is located in

the housing and moves up or down as the load on the handle is varied. The readings reflect the load at any particular moment. The trafficability penetrometer\* is similar to the airfield penetrometer (it has an additional cone size) and can be used to make the same measurements, except for scale readings. However, the trafficability instrument is not as portable or as rugged as the airfield penetrometer. The airfield penetrometer is light enough and compact enough to be readily carried by an individual as supplemental equipment and is capable of withstanding rough handling during transport, or when used in reconnaissance and construction control work. The trafficability penetrometer, on the other hand, has a more finely divided scale which permits more accurate readings.



Fig. 1. Airfield penetrometer in use

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\* See Department of the Army Technical Bulletin TB ENG 37, dated 10 July 1959.



## Use

7. Before the airfield penetrometer is used, it should be inspected to see that all joints are tight and that the load indicator reads 0. To operate the penetrometer, the hands are placed symmetrically on the handle, palms down, as shown in fig. 1. Force is applied to the handle (with the operator's arms steadied against his thighs) until a slow, steady, downward movement of the instrument occurs. The load indicator is read at the moment the base of the cone enters the ground (surface reading) and at desired depths at the moment the corresponding depth mark on the shaft reaches the soil surface. A reading is made by shifting the line of vision from the soil surface to the indicator just before the desired depth is reached. Maximum efficiency is obtained with a two-man team in which one man operates the penetrometer, informing the other when the desired depths are achieved. The other man reads the instrument's load indicator and records the values. It is also possible for one man to operate the instrument and record the measurements by stopping the penetration at any intermediate depth, recording previous readings, and then resuming penetration.

8. Observance of the following rules is important in obtaining accurate data:

- a. The instrument should read 0 when suspended by the handle and 15 when a 150-lb load is applied.
- b. The cone and rod should be inspected and cleaned prior to each use.
- c. The instrument should be kept in a vertical position while in use.
- d. The rate of penetration should be about 1/2 to 1 in. per sec; however, slightly faster or slower rates will not materially affect the readings.
- e. If it is suspected that the cone is encountering a stone or other foreign body at the depth where a reading is desired, another penetration should be made nearby.
- f. The readings should be taken at the proper depths. Carelessness in determining proper depth is one significant source of error in the use of the penetrometer.

## Maintenance

9. The airfield cone penetrometer is simply constructed of durable

metals and needs little care other than cleaning and oiling. The calibration should be checked occasionally. As noted earlier, the load indicator should read 0 when the instrument is suspended by the handle and 15 when a 150-lb load is placed on the handle. If an error exceeding about 5 percent is noted the penetrometer should be recalibrated.

#### Soil-Strength Evaluation with Airfield Penetrometer

10. The number of measurements to be made, the location of the measurements, and other such details vary with each area to be examined and with the time available. For this reason, hard and fast rules for evaluating an airfield are not practicable, but the following instructions will be useful. The information in the following paragraphs applies primarily to fine-grained soils (silts, clays, etc.) except for paragraph 17 which offers comments on coarse-grained soils (sands).

##### Range of readings

11. The airfield penetrometer has a range of 0 to 15. A reading near 0 can occur in a very wet soil, which, of course, cannot support traffic. A reading approaching 15 will occur in dry, compact clays or silts and tightly packed sands or gravels. Most aircraft that might be required to use an unpaved area could easily be supported for a substantial number of landings and takeoffs by a soil having an airfield index of 15.

##### Number of measurements

12. Soil conditions are extremely variable; therefore, as many penetrometer measurements should be taken in a given area as time and circumstances will permit. The strength range and uniformity of the area will control the number of measurements necessary. Areas which are obviously too soft for emergency landing strips will be revealed after a few measurements, as will areas with strengths that are more than adequate. In all areas, it is advisable to test the softest-appearing spots first, since the softest condition controls the suitability of the area. Soft spots are not always readily apparent, however, and if the first test results indicate barely adequate strength, the entire area should be examined. Penetrations in areas that appear to be firm and uniform may be few and widely spaced, e.g. approximately every 200 ft along the proposed center line. In areas

of doubtful strength, the penetrations should be more closely spaced, and areas on both sides of the center line should be investigated. No less than three penetrations should be made at each location, and usually five are desirable. If time permits or if inconsistencies are apparent, as many as 10 penetrations should be made at each test location.

Depths at which readings should be made

13. Soil strength usually increases with depth, but in some cases a thin, hard crust will overlie a deep, soft layer or the soil will contain thin layers of hard and soft material. For this reason, it is recommended that each penetration be made to a 24-in. depth unless prevented by a very firm condition at a lesser depth. When penetration cannot be made to the full 24-in. depth, a hole should be dug or augered through the firm material and penetrometer readings should be taken in the bottom of the hole to ensure that no soft layer underlies the firm layer. If possible, readings should be taken every 2 in. from the surface to a depth of 24 in. Generally, the surface reading should be disregarded when readings are averaged to obtain a representative airfield index.

14. In the normal soil condition, i.e. when strength increases with depth, the readings at the 2- to 8-in. depths (4 to 10 in. for dry sands and for soil that will be trafficked by larger aircraft) should be used to designate the soil strength for airfield evaluation. If readings in this critical layer at any one test location do not differ more than 3 or 4 units, the arithmetic average of these readings can be taken as the airfield index for the area represented by the readings. When the range between the highest and lowest readings is more than about 4, the interpreter of the data must use his judgment in arriving at a rating figure. It is suggested that he lean toward the low readings for conservatism.

15. In an area in which a hard crust less than about 4 in. thick overlies a much softer soil, the readings in the crust should not be used in evaluating the airfield. For example, if a 3-in.-thick crust results in an average reading of 10 at the 2-in. depth while the average reading is 5 below 3 in., the area should be evaluated at 5. If the crust is more than about 4 in. thick, it will probably aid in supporting aircraft, but the readings below the crust should also be considered in the evaluation. For example, if the crust in the above instance is 5 in. thick, the rating

of the field would then be about halfway between the 10 of the crust and the 5 of the underlying soil, or, conservatively, 7. Innumerable combinations of crust thickness and strength and underlying soil strength can occur. Sound reasoning and engineering judgment should be used in evaluating such areas.

16. In an area in which a very soft, thin layer is underlain by a firmer layer, the evaluation also is a matter of judgment. If, for example, 1 to 2 in. of soil with airfield index averaging about 5 overlies a soil with an index of 10, the field can be rated at 10. But if this soft layer is more than about 4 in. thick, the field should probably be rated at 5. Areas of fine-grained soils with very low readings in the top 1 in. or more are likely to be slippery or sticky, especially if the soil is a clay.

#### Special treatment for sands

17. Many sands occur in a loose state. Such sands when relatively dry will show increasing airfield indexes with depth, but the 2-in.-depth index will often be low, perhaps about 3 or 4. Such sands usually are capable of supporting aircraft whose requirements are much higher than an airfield index of 3 or 4, because the strength of the sand actually increases under the confining action of the aircraft tires. Generally, any dry sand or gravel will be adequate for aircraft in the C-130 class (60- to 80-psi tire-inflation pressure), regardless of the penetrometer reading. This is also true for smaller aircraft with tire-inflation pressures in the 20- to 30-psi range. All sands and gravels in a "quick" condition (water percolating through them) must be avoided. Evaluation of moist sands should be based on the penetrometer readings obtained as described earlier.

#### Dry lake beds

18. Much data have been collected from dry lake beds in the southwest United States for use in correlating CBR and airfield index. A study of these data has shown that the correlation used in this report is not applicable to some of these sites, particularly in the high airfield-index range. The CBR's at these latter sites tend to be somewhat lower than those indicated by the correlation presented herein. Thus, particular care should be exercised when using the airfield index of dry lake beds and, if possible, field CBR data should be obtained.

### Effects of weather on evaluation

19. Because soil conditions are immediately and significantly affected by weather, an evaluation is valid only for the period immediately after measurements are made. However, it usually can be assumed that the evaluation will remain constant as long as no rain occurs.

### Application of Data Obtained

#### General application

20. Once the airfield index for a given landing strip is established, its relation to aircraft load, tire-inflation pressure, and anticipated number of coverages (a measure of load repetitions) must be determined. Relations of airfield index to these factors have been established from data gathered over many years. Plate 2 is a nomograph relating single-wheel or equivalent single-wheel load, tire pressure, airfield index, and coverages. If the load and tire pressure of the aircraft and the airfield index are known, it is possible to enter plate 2 and determine the number of coverages that can safely be made by the aircraft. Plate 3 presents the procedure for determining the equivalent single-wheel load of aircraft having multiple-wheel assemblies.

21. Table 1 shows the required airfield index for 1 to 1000 passes of some of the more common types of cargo aircraft. In using plate 2 directly, allowable coverages can be determined. However, this determination must be converted to aircraft passes for ultimate use. The relation of passes to coverages depends on the number, width, and spacing of wheels on an aircraft as well as the degree to which the aircraft can be expected to wander left and right of a central position. In nearly all cases, it is adequate to estimate the pass-per-coverage ratio from the following tabulation which shows the number of passes per coverage of four aircraft gear configurations.

<u>Gear Configuration</u>	<u>No. of Passes per Coverage</u>
Single wheel	5
Twin wheel	3-1/2
Single tandem	2
Twin tandem	2

Table 1

Required Airfield Index for Common Cargo Aircraft

<u>Aircraft</u>	<u>Gross Aircraft Weight lb</u>	<u>Tire-Inflation Pressure psi</u>	<u>Normal Load on Single Wheel of Main Gear lb</u>	<u>No. of Passes</u>	<u>Airfield Index Required</u>
C-47	31,000	50	14,000	1-3	3.2
				25	3.8
				250	4.9
				1000	5.8
C-119	66,600	70	15,000	1-3	3.9
				25	5.0
				250	6.5
				1000	7.5
C-123	58,100	85	26,100	1-3	4.9
				25	5.9
				250	7.5
				1000	8.6
C-124	175,000	65	39,400	1-3	6.2
				25	7.6
				250	9.7
				1000	11.2
C-130	116,000	60	26,100	1-3	3.9
				25	5.3
				250	7.0
				1000	7.9
C-130	135,000	80	30,000	1-3	5.2
				25	6.9
				250	8.7
				1000	10.1
C-133	275,000	95	31,000	1-3	7.0
				25	9.0
				250	11.4
				1000	13.2
C-135	276,000	125	31,000	1-3	7.2
				25	9.5
				250	12.0
				1000	13.9
C-141	317,000	185	35,700	1-3	9.4
				25	12.3
				250	--
				1000	--

Specific determinations can be made using methods given in WES Miscellaneous Paper No. 4-459, Ground Flotation Requirements for Aircraft Landing Gear, dated July 1965. Lateral traffic distribution widths measured directly in the field are described in WES Technical Memorandum No. 3-426, Study of Channelized Traffic, dated February 1956.

#### Warning

22. Users of the information in this report are warned of its limitations. The curves and tabular information in plate 2 and table 1 are based on correlations of aircraft performance and airfield indexes. Unfortunately, these are not exact correlations uniquely relating aircraft performance to airfield index. As soils vary in type and condition from site to site, the relation of airfield index to aircraft performance also varies. For this reason, the curves in plate 2 and the data in table 1 will not in all cases accurately predict performance. These relations have been selected so that in nearly all cases aircraft performance will be at least that indicated. However, it should be recognized that on occasion performance may not be quite as good as that indicated.

#### Sample problem

23. To assist the user of this report, a sample problem and its solution are presented as follows:

Problem: Can 20 C-124 aircraft make three deliveries each to a site having an airfield index of 12?

Given: The gross weight of the aircraft is 175,000 lb; the tire pressure is 65 psi. The twin-wheel assembly has 44-in. center-to-center (c-c) spacing.

#### Solution:

20 aircraft  $\times$  3 deliveries  $\times$  2 passes/delivery = 120 passes

$$\frac{120 \text{ passes}}{3-1/2 \text{ passes coverage}^*} = 34 \text{ coverages}$$

To determine equivalent single-wheel load (ESWL), the procedure described in plate 3 is used:

---

\* From tabulation in paragraph 21.



Tire-inflation pressure = 65 psi  
 Single-wheel load (SWL) = 39,400 lb (from table 1)  
 Tire contact area (A) =  $\frac{39,400}{65} = 606$  sq in.

Next, the radius of a circle having an area of 606 sq in. is determined:

$$\text{Equivalent radius (r)} = \left(\frac{A}{\pi}\right)^{1/2} = \left(\frac{606}{3.14}\right)^{1/2} = 13.9 \text{ in.}$$

Knowing the equivalent radius of 13.9 in. and the c-c wheel spacing of 44 in., it is possible to get the spacing in radii:

$$\text{c-c wheel spacing in radii} = \frac{44 \text{ in.}}{13.9 \text{ in./radius}} = 3.16 \text{ radii}$$

Next, determine the increase in SWL for adjacent wheel = 27 percent (from curve in plate 3)

$$\begin{aligned} \text{Therefore, ESWL} &= 1.28 \times \text{SWL} \\ &= 1.28 \times 39,400 \end{aligned}$$

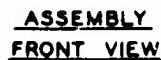
$$\text{ESWL} = 50,400$$

$$\text{Tire pressure} = 65 \text{ psi}$$

Airfield index required for 34 coverages = 9.0 (from plate 2)

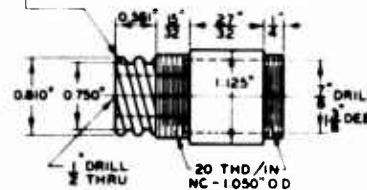
Answer: Operations are safe, since required airfield index (9.0) is less than available airfield index (12).

SCALE SCRIBED AFTER COMPLETE PENETROMETER  
ASSEMBLY CALIBRATED ON LOAD TESTING MACHINE.  
LOADS REFERENCED TO TOP OF LOAD INDICATOR  
LUG FACE. MINIMUM INTERVALS AT 10 LB. SCRIBED  
1/8" LONG ON FACE OF TUBE. 0 AND 50 LB. INTERVALS  
1/4" LONG. A. INDICATED. 150 LB. MAXIMUM READING.  
CURVES TO BE 1/8" HIGH.



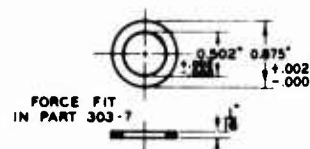
TYPE 303 STAINLESS - 1 REQ'D

DOUBLE END - EACH ON" FULL  
TURN CUT OFF SQ. - 0.330" PITCH  
RIGHT HAND - MUST PROVIDE FIRM  
FITS WITHOUT CAUSING ANY  
DISTORTION TO THE SPRINGS THE  
SPRING CUP DIM. MAY VARY  
SLIGHTLY DUE TO IRREGULARITIES  
IN THE SPRING DIM. AND PITCH



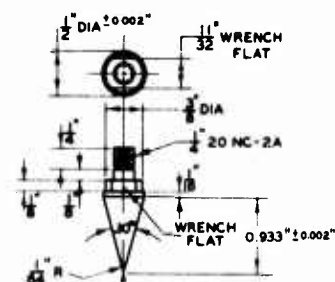
**LOWER SPRING CUP & BUSHING**  
**HOUSING - 303-7**

TYPE 303 STAINLESS 1 REQ'D



WASHER - 303-9

TYPE 303 STAINLESS - 1 REQ'D

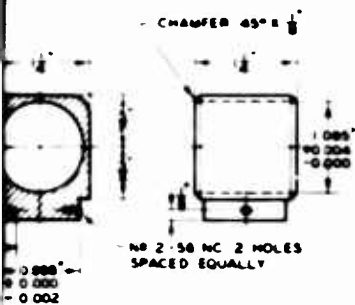


CONE - 303-12

TOOL STEEL , AISI - D2 - 2 REQ'D  
HARDENED TO ROCKWELL C 58 - 62

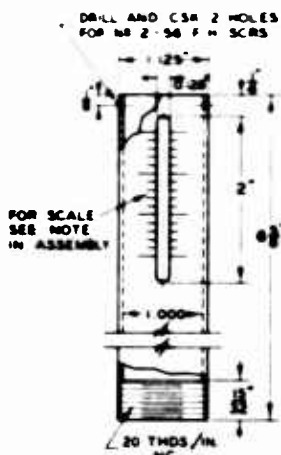
NOTE :

STANDARD COMMERCIAL ITEMS: MIDGET OPEN-  
END WRENCHES DOUBLE HEAD, 15° AND 75° HEADS.  
ALLOY STEEL, HEAT TREATED, CHROME PLATED  
OVER NICKEL, FACES POLISHED. OVERALL LENGTH  
3 3/4 IN, NOMINAL OPENINGS 1/32 IN. MILITARY  
DESCRIPTION: GGG-W-838A-1 TYPE XX STYLE B 2 REQUIRED



**HEAD-303-2**

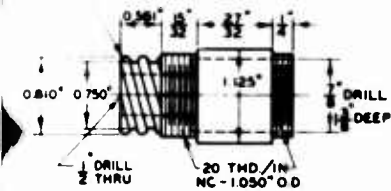
TYPE 303 STAINLESS - 1 REQ'D



**HOUSING-303-3**

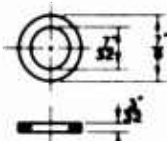
TYPE 303 STAINLESS - 1 REQ'D

DOUBLE THD - EACH ONE FULL TURN CUT OFF SQ - 0.350" PITCH - RIGHT HAND - MUST PROVIDE FIRM FITS WITHOUT CAUSING ANY DISTORTION TO THE SPRINGS THE SPRING CUP DIM. MAY VARY SLIGHTLY DUE TO IRREGULARITIES IN THE SPRING DIM. AND PITCH



**LOWER SPRING CUP & BUSHING HOUSING-303-7**

TYPE 303 STAINLESS - 1 REQ'D



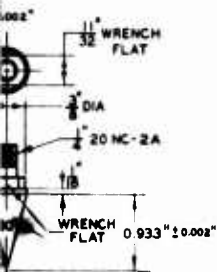
**SEAL-303-8**

FELT - 1 REQ'D



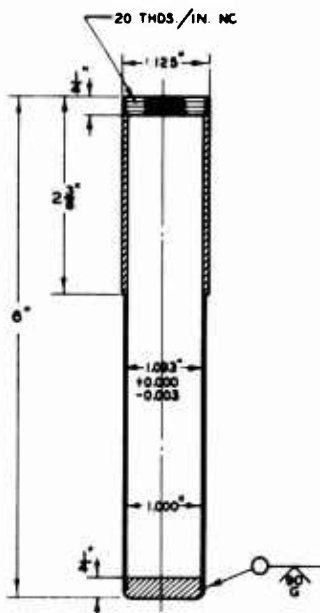
**HER-303-9**

STAINLESS - 1 REQ'D



**-303-12**

AL, AISI-D2-2 REQ'D  
O ROCKWELL C 58-62



**CONE COVER AND HANDLE-303-10**

TYPE 303 STAINLESS - 1 REQ'D



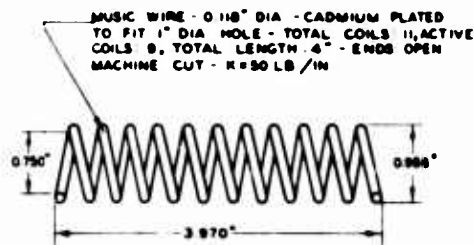
**LOAD INDICATOR-303-4**

BRASS - 1 REQ'D



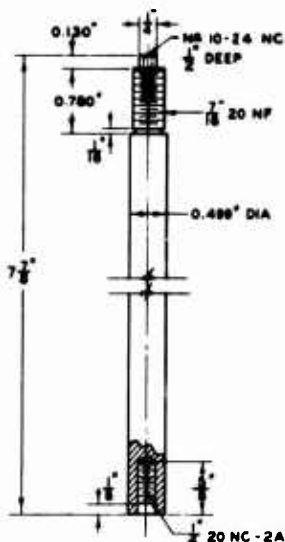
**UPPER SPRING CUP-303-5**

TYPE 303 STAINLESS - 1 REQ'D



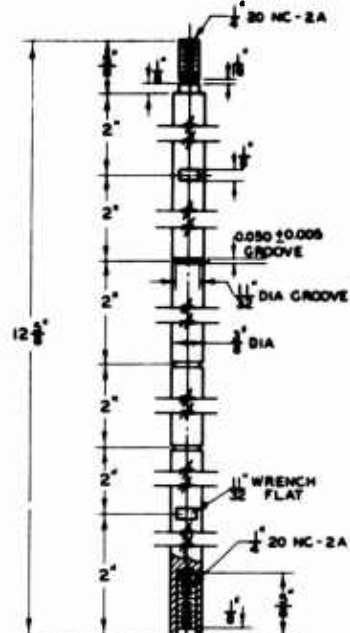
**TENSION SPRING-303-6**

2 REQ'D



**CONE ROD-303-11**

TYPE 303 STAINLESS - 1 REQ'D  
GROUND AND POLISHED



**ROD EXTENSION**

TYPE 303 STAINLESS - 2 REQ'D

NOTE:  
REFER TO SPECIFICATIONS FOR  
CALIBRATION PROCEDURE OF  
COMPLETED INSTRUMENT.



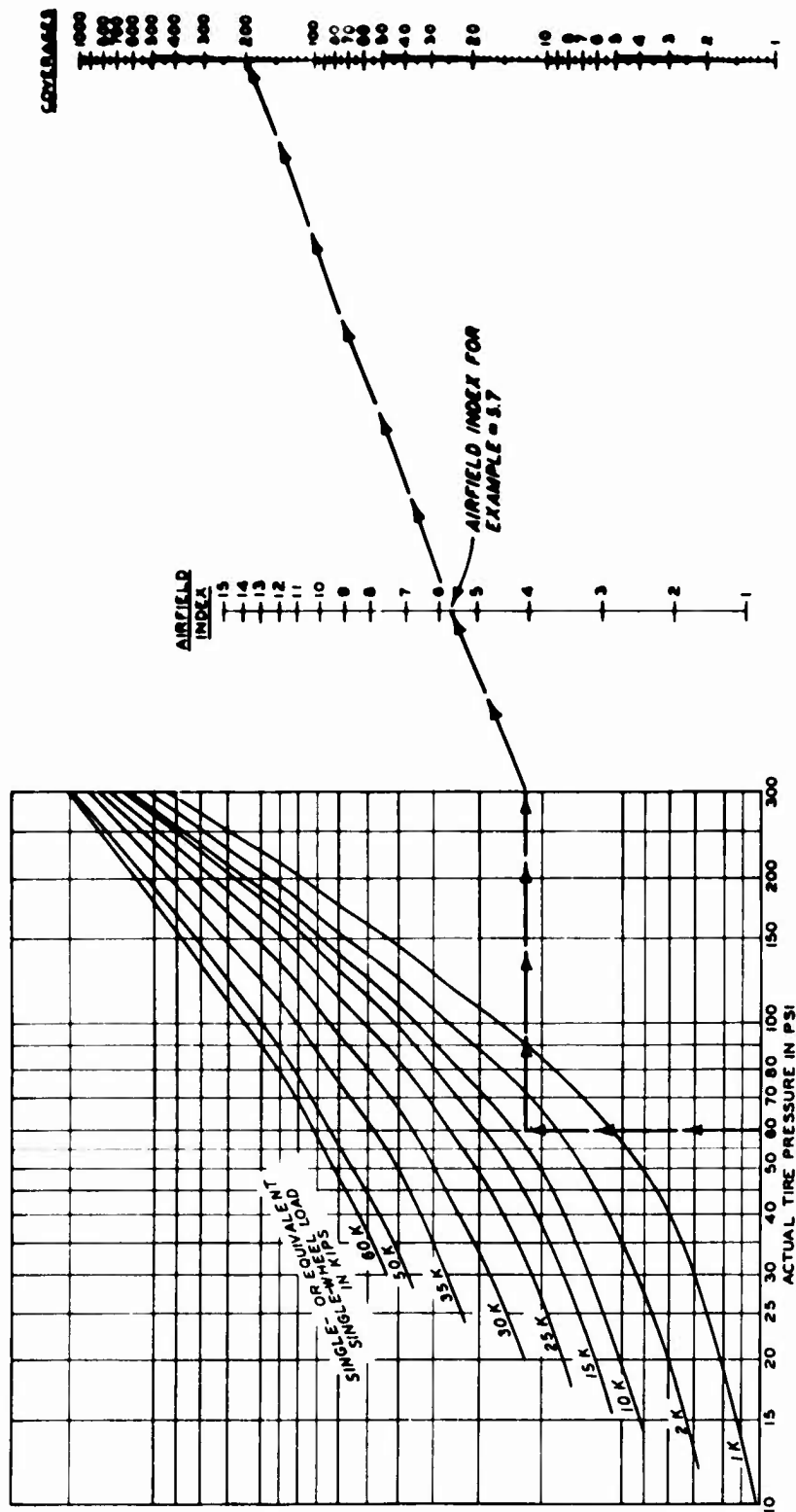
REVISED 9/85  
DATE: JAN. 1985

**AIRFIELD CONE  
PENETROMETER**

U. S. ARMY ENGINEER  
WATERWAYS  
EXPERIMENT STATION  
CORPS OF ENGINEERS  
VICKSBURG, MISS

**MS-303-1**

SHEET 1 OF 1



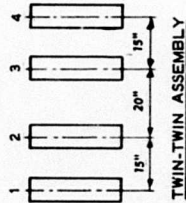
EXAMPLE: GIVEN 60-PSI TIRE PRESSURE AND  
8-KIP SINGLE-WHEEL LOAD.

AIRFIELD INDEX REQUIRED FOR  
200 COVERAGES = 5.7.

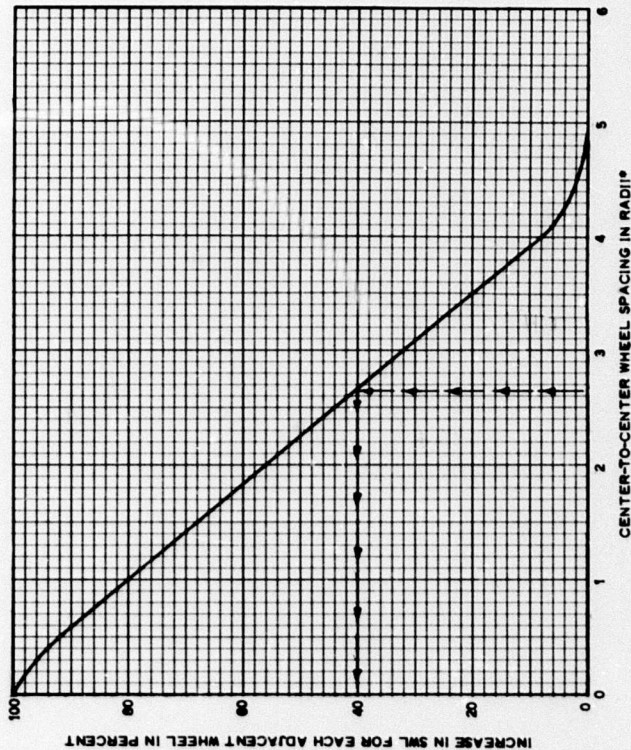
## AIRFIELD INDEX REQUIRED FOR OPERATION OF AIRCRAFT ON UNSURFACED SOILS

R03085A

**PROCEDURE FOR DETERMINING THE ESWL FOR  
MULTIPLE-WHEEL ASSEMBLIES**



ASSEMBLY LOAD = 100,000 LB  
 TIRE CONTACT AREA (A) = 100 IN.<sup>2</sup>  
 SINGLE-WHEEL LOAD (SWL) =  $\frac{\text{ASSEMBLY LOAD}}{\text{NO. OF WHEELS ON ASSEMBLY}}$   
 SWL = 25,000 LB  
 $A = 100 \text{ IN.}^2 = \pi r^2$   
 $r = \sqrt{\frac{A}{\pi}} = \sqrt{\frac{100}{\pi}} = 5.65 \text{ IN.}$



NOTE: \* ANY WHEEL SPACED 4 RADII (CENTER TO CENTER) OR GREATER FROM A PARTICULAR WHEEL IS CONSIDERED TO HAVE NO EFFECT ON THE ESWL FOR THAT WHEEL.  
 \*\* VALUES READ FROM CURVE AS INDICATED BY ARROWS.

**DETERMINE EQUIVALENT SINGLE-WHEEL LOAD (ESWL)  
FOR WHEEL NO. 2**

WHEEL NUMBER	CENTER-TO-CENTER SPACING INCHES	RADI	INCREASE IN SWL PERCENT
1	15	2.65	40.2**
2			
3	20	3.54	19.0
4	35	6.19*	
TOTAL			59.2

$$\text{ESWL} = 1.592 \times \text{SWL} = 39,800 \text{ LB}$$

UNLESS THE LOCATION OF THE MAXIMUM ESWL IS OBVIOUS, THE ESWL FOR EACH WHEEL OF THE ASSEMBLY AND AT THE CENTER OF THE ASSEMBLY WILL BE DETERMINED IN ORDER TO OBTAIN THE MAXIMUM ESWL FOR A GIVEN ASSEMBLY.

**THEATRE OF OPERATIONS  
AIRFIELDS**  
**CURVE FOR DETERMINING THE  
EQUIVALENT SINGLE-WHEEL LOAD  
FOR MULTIPLE-WHEEL ASSEMBLIES**